

Understanding X-ray Timing and Radio Observations Of Jet Sources

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Abstract. Time-dependent x-ray and radio observations of accreting sources give considerable insight into how jets might be produced, both in low-luminosity and high-luminosity situations. I discuss recent observations of binary x-ray sources and AGN that may have a direct bearing on jet production, and I review the theoretical efforts that have been made to understand them. While it is certainly true that jet production can be understood only with a good accretion model, I also argue that accretion onto compact objects cannot be understood without fully taking into account the production of a jet. Jets are probably a fundamental aspect of some accretion modes.

In a quest for an integrated model for accretion and jet production I introduce a new accretion concept, the magnetically-dominated accretion flow or MDAF, as an alternative to current models for the low/hard/plateau state of accreting black holes (and the atoll source island state). Although much quantitative work needs to be performed before the concept can evolve into a true model, MDAFs have a number of phenomenological advantages. In addition to providing explanations for several X-ray timing and radio properties of accreting sources, the MDAF suggests a model for the infrared flares in the Galactic center.

INTRODUCTION

There are two possible approaches to giving a review of X-ray and radio observations of jets: 1) discuss jet *flow* at a considerable distance from the central engine and 2) discuss jet *production* that occurs in or near the compact object. The first approach is the standard one often taken in (mainly AGN) jet studies and involves superluminal motion, beaming, synchrotron and Compton emission processes, *etc.* While a very interesting field, this approach does not have much to do with X-ray timing observations on very short time scales. On the other hand, the second aspect of jets (their production) is potentially *directly* accessed by XTE *and* by correlated radio observations. I therefore will take the second approach. As jets are believed to be produced as a byproduct of accretion onto compact objects such as black holes and neutron stars, a discussion of this type will necessarily include accretion processes as well.

Below I present a review of the theory of accretion and jet production, followed by a brief review of some X-ray timing and radio observations that appear relevant to jet production. I then will present some new ideas on where and how I believe that research in this field should proceed, along with a possible new accretion/jet-production scenario for jetted sources — the magnetically-dominated accretion flow or MDAF. While serious quantitative investigation of these ideas eventually may render some of them untenable, nevertheless it seems clear that a full consideration of *strong*

magnetic fields in accreting sources should help to explain some of the puzzling observed properties of black hole and neutron star systems that produce jets.

A BRIEF REVIEW OF ACCRETION AND JET-PRODUCTION PROCESSES

Accretion Theory

Classical Accretion Disk Models

In their original paper, and in a fashion reminiscent of stellar structure, Shakura & Sunyaev [30], hereinafter SS, identified three main regions within a high-luminosity accretion disk (one within, say 10% of the Eddington luminosity or so): 1) the outer region, in which pressure is dominated gas pressure p_g and opacity is dominated by free-free absorption κ_{ff} ; 2) the middle region, dominated by p_g and electron scattering opacity κ_{es} ; and 3) the inner region, dominated by radiation pressure p_r and κ_{es} . At lower luminosities (and, consequently, lower accretion rates), the inner p_r -dominated region would disappear, and the 'middle' region would extend all the way to the accreting neutron star or black hole. At very low accretion rates, only the 'outer' region would remain, with the entire disk characterized by gas pressure and free-free absorption.

In recent years this picture has given way to related,

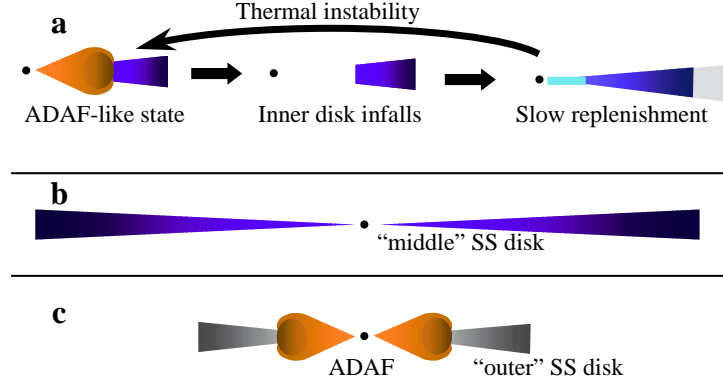


FIGURE 1. Simple view of modern accretion theory. The Shakura & Sunyaev view of relatively cool inner, middle, and outer disk regions has given way to the following: a) at high accretion rates an “inner” radiation-pressure-dominated region exists, which is thermally unstable to forming a rapidly-accreting hot disk center (qualitatively identified as the ‘very high unstable state’); b) at moderate accretion rates, where the “middle” region dominates the disk center, the accretion is stable (identified as the ‘high/soft state’); c) at low accretion, where gas pressure and free-free absorption dominate, the central disk region bloats into a rapidly-accreting, advection-dominated flow (ADAF). The latter has been identified as the low/hard or ‘plateau’ accretion state.

but more realistic, accretion scenarios at both low and high accretion rates. Ichimaru [11], and later Narayan & Yi [25], showed that a two-temperature, advection-dominated accretion flow or ADAF solution obtains at low accretion rates ($\dot{M}/\dot{M}_{Edd} \lesssim 0.1$) near the center of the accretion disk, giving rise to an emitted hard (~ 100 keV) X-ray spectrum that may explain the ‘low/hard’ state of X-ray binaries. The standard ‘outer’ disk solution still may obtain at larger radii where the disk is cooler. The disk radius at which the accretion changes from the SS-type flow to an ADAF-type flow is called the ‘transition radius’ r_{tr} . (See Figure 1c.)

In the high accretion rate case ($\dot{M}/\dot{M}_{Edd} \gtrsim 0.3$), Shakura & Sunyaev [31] and Pringle [28] showed that, when the radiation-pressure-dominated inner region exists, that part of the disk is thermally unstable. Some 1-D numerical models by [32] show that a possible nonlinear behavior of such disks is that the inner region bloats into a gas-pressure-dominated, optically-thin, geometrically-thick region that is not unlike an ADAF. However, this region then accretes onto the compact object at a much faster rate (*i.e.*, on a thermal time scale) emptying the inner region of the disk much faster than it can be replenished by accretion from the middle region. (See Figure 1a.) The inner region is then slowly filled, on the longer secular (accretion) time scale, whereupon that portion of the disk, now radiation-pressure-dominated again, bloats once more into an ADAF-like state, repeating the cycle. This predicted behavior is similar to that actually seen

in the ‘very high state’ in sources such as GX 339-4 and GRS 1915+105.

Only at moderate accretion rates ($0.1 < \dot{M}/\dot{M}_{Edd} < 0.3$) does a standard SS-type accretion model appear to be a good model for the actual observed source. (See Figure 1b.) In the ‘high/soft’ state binary X-ray sources appear to be relatively cool and thermal, with stable geometrically thin, optically thick disks.

The Magneto-Rotational Instability as a Viscosity Mechanism

One of the main deficiencies of the above classical accretion theory is that one has to assume an effective viscous stress that is proportional to the local pressure. The proportionality constant, called α , is generally taken to be in the range 0.01-1.0, and the ‘viscous’ angular momentum transport was thought to be due either to turbulence or magnetic stresses. A value of $\alpha \sim 0.01$ appears to be typical of thin accretion disk flows, while $\alpha \sim 0.3 - 1.0$ is more typical of ADAFs.

Balbus & Hawley [1] showed that a magneto-hydrodynamic (MHD) instability that occurs in shear flow with *weak* ($\alpha < 1.0$) magnetic fields can account for the transfer of angular momentum in accretion flows. In the nonlinear regime, the ‘magneto-rotational-instability’ or MRI creates MHD turbulence that accounts for about 75% of the angular momentum

transport, with magnetic stresses accounting for the remainder. Accretion disks, therefore, are thought to be seething, turbulent entities, with tangled magnetic fields pervading, and probably protruding from, the main accretion flow. Thin SS-type disks will be optically thick, with only the disk photospheric region observable, whereas ADAFs will be optically thin, with the entire turbulent process visible in the X-ray spectral and timing observations.

It is important to note that, as the strength of the magnetic field increases ($\alpha \rightarrow 1$), the magnetized plasma becomes more stable, the field becomes more ordered, and the B-H instability is suppressed.

Concerns Regarding ADAF Models

Recently some concerns have been raised about the ability of an ADAF to maintain a two-temperature structure [2]. The principal argument is that MHD turbulence may couple the ions and electrons dynamically, allowing for a strong heat flow between the supposedly hot ($\sim 10^{11-12}$ K) ions and cooler ($\gtrsim 10^9$ K), radiating electrons. Currently, this controversy is an open question [29, 26], but if ADAFs *are* found to have strong ion-electron thermal coupling, then they would not be able to maintain their bloated and optically thin nature nor their hot, $\gtrsim 100$ keV spectrum. That is, ADAFs would no longer be good models for the low/hard X-ray state. It therefore will be important to resolve this controversy in the near future.

Another concern is that ADAF models require very high α viscosity coefficients. That is, they predict magnetic fields that are so strong that they are near the suppression limit of the B-H instability. It is quite possible that the MHD turbulence in a strong-field ADAF often will be suppressed to the point where angular momentum is carried only by magnetic stresses.

Jet Production

Classical Jet Production Models

In the standard electrodynamic picture of jet production, ionized plasma in an accretion flow is accelerated and collimated by the forces generated by rotating *large-scale* electromagnetic fields that are anchored in the accretion disk [4, 33, 22]. Thus, the conditions that promote jet production are the antithesis of those that promote turbulent angular momentum transport in disks. Specifically, the global magnetic field is wound around the rotation axis, pushing plasma up and out of the disk region and then collimating it with a standard 'Z-pinch'.

Gas pressure forces first accelerate the flow to the local slow magnetosonic flow speed along the magnetic field lines. Beyond the slow point the large, rotating torsional Alfvén wave accelerates the flow to the local Alfvén speed, followed by final acceleration to the local fast magnetosonic speed by the magnetic pressure gradient.

It is important to realize that, in most jetted sources, the outflow is probably poorly collimated near the central engine. When the above magnetic wind reaches a steady state, the base of the jet is quite broad before it is collimated over several hundred Schwarzschild radii [13, 35] into a slender jet. This effect may have been seen in very high resolution radio observations of M87 [12].

The Jet - Thick Disk Connection

Recently, it has been discovered that the ejection of a jet depends strongly on the character of the accretion flow [8]. Specifically, strong jets do not appear to be produced in the high/soft state when the disk is geometrically thin and cool. On the other hand, in the low/hard state, a strong and steady jet outflow is observed. And, in the very high state, very powerful and *unsteady* jets are observed in sources like GRS 1915+105 and GX 339-4.

This behavior has been explained theoretically [21, 23] as follows. If the jet is accelerated in the accretion disk or corona, the strength of the jet will be proportional to the square of the strength of the poloidal magnetic field B_p , which will be a fraction of the strength of the total toroidal magnetic field B_ϕ in the disk

$$L_{jet} \propto B_p^2 \approx B_\phi^2 \frac{H^2}{R^2} \quad (1)$$

where H/R is the ratio of the scale height to the local cylindrical radius in the disk. If the disk is geometrically thin ($H \ll R$), the poloidal field, and the jet strength, will be small. Thin disk therefore may produce jets, but they will be weak. On the other hand, if the disk is geometrically thick ($H \sim R$), then the jet should be strong. This explanation also supports the picture in Figure 1 where the disk is bloated temporarily in the very high state limit cycle and bloated semi-permanently in the low/hard state. It is this bloating that contributes to the production of the jet.

Disk Ejection vs. Disk Accretion in an Unstable Jet Event

Several sources in the very high state (GRS 1915+105, GX 339-4, 3C 120) show 'dips' in the 2-10 keV region of the X-ray spectrum just before the ejection of a relativistic radio jet [27]. This has been interpreted as a temporary disappearance of the central, cool accretion flow —

a 'hole' in the disk. There are two possible physical interpretations of this important result: 1) most of the central portion of the disk has been *ejected* in the jet outflow or 2) the central region of the disk has been rapidly *accreted* into the black hole due to a disk instability.

The difference between these two interpretations is subtle but very important. There are two problems with the 'disk ejection' interpretation (the one that is generally invoked by most investigators). First of all, concluding that the disk is ejected in these unsteady jet-production events in the very high state implies that there must be two different types of jet-production mechanisms at work in X-ray binaries. One is a stable one at work in the low/hard state that does *not* eject the central regions of the disk. The other is an unstable one that *does* eject the central disk, forcing the X-ray dip until the disk is replenished by the accretion flow. Having to explain two different jet-production mechanisms would be a very difficult task. Secondly, and perhaps more importantly, the ejection of most of the central disk region in a *relativistic* flow would be impossible in most accretion scenarios. The accretion energy of such an event could be no more than a moderate fraction of the rest energy of the central disk matter itself. (This is the case even if some of the energy is extracted from a central rotating black hole.) However, in order to eject *all* the central disk in a jet with a Lorentz factor of several or more, we would need considerably *more* energy than is available in that material's own rest mass. Ejecting the entire inner disk relativistically, therefore, is energetically impossible.

Interpreting unsteady jet ejections as rapid disk *accretion* events has a number of advantages. First of all, in this scenario a substantial portion of the binding energy of all the accreting material is now available for jet acceleration, while only a small portion of the matter is needed to form the jet. The jet speed, therefore, can be quite relativistic. Secondly, we now need only one jet-production mechanism (the classical one described earlier) in both the low/hard and very high state. In the latter case the disk disappearance is caused by the already-recognized thermal instability of the radiation-pressure-dominated inner region which has become bloated and rapidly accretes. A quasi-steady jet is produced by a strong large-scale magnetic field, but only while the rapid geometrically thick accretion flow continues. After the bloated disk has fully accreted, jet production subsides and replenishment of the central region via thin disk accretion commences. The disk accretion interpretation of the apparent hole in the disk is not only the simpler of the two interpretations, it also is the more physically plausible one.

The Need for an Integrated Model

There therefore is strong evidence that not only are jets produced by accretion flows, but the strength and character of the jet is determined by the nature of that flow. Yet, while the basics of accretion appear to be fairly well in hand, and the basics of jet production also appear to be reasonably understood, it still is the case that not a single integrated model or simulation exists that adequately shows how a magnetized accretion disk, operating under the Balbus-Hawley viscosity, can produce an MHD jet. Virtually all global disk models and simulations of the MRI do *not* produce strong electromagnetically-driven jets. Only one such simulation [10] appears to have produced a jet, and that outflow was driven by gas pressure in a manner more similar to the Blandford-Begelman advection-dominated inflow-outflow solutions (ADIOS) [3] models than to classical electromagnetic acceleration ones. The inability of accretion models to produce jets, and the inability of jet production models to fit into the accretion scenario, is perhaps the chief problem facing the study of X-ray binaries and active galactic nuclei today.

X-RAY AND RADIO OBSERVATIONS OF ACCRETING, JET-PRODUCING SYSTEMS

The Low/Hard (Plateau) State: ADAFs and JDAFs

In the low/hard spectral state of black hole candidate systems (sometimes called the 'plateau' state) the X-ray/ γ -ray spectrum peaks at about 100 keV and is up to an order of magnitude weaker at lower X-ray energies (2-10 keV), and at higher γ -ray energies (> 1 MeV), than it is in the high/soft state [20, 15]. This has been interpreted as the replacement of the cool central disk regions with a hot ($\sim 10^9$ K), geometrically thick, optically thin ADAF [25], as shown in Figure 1c.

Atoll X-ray binaries (sources with weakly-magnetized [$< 10^{8-9}$ G] neutron stars instead of black holes) also possess X-ray states similar to the low/hard and high/soft states called, respectively, the 'island' and 'banana' states [34, 6]. This indicates that, in the absence of a strong pulsar magnetic field, the accretion disk around a neutron star acts similarly to that around a black hole.

However, the recognition that a steady jet is almost always associated with the low/hard state [8, 24] has prompted a modification of the ADAF model to include a jet base *plus* a fast collimated jet outflow in addition to a hot thick disk [17, 18]. (See Figure 2.) The jet-disk model not only fits the spectrum of a number of

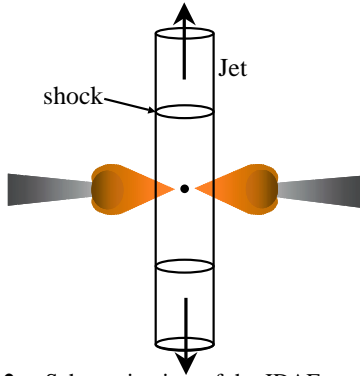


FIGURE 2. Schematic view of the JDADF model (after [38]). An SS disk gives way to an ADAF in the central regions, as in Figure 1. A jet then emanates from the ADAF center, whereupon it shocks some distance above the disk. The nonthermal jet is responsible for emission from radio to far IR and from hard X-ray to γ -ray. The disk, when strong, produces mainly thermal emission from IR to X-ray.

sources well, including low-luminosity AGN (LLAGN) [19, 7], it also predicts the radio/X-ray correlation that characterizes sources in the low/hard state [5]. (See also the paper by S. Corbel in these proceedings.) In these models the emission from the jet sometimes dominates that from the disk so much that they are often referred to as jet-dominated accretion flows or JDADFs [7].

The JDADF model is important in helping us gain some insight into the generation of the broad-band spectrum and in possibly understanding the morphology of the accreting system in the low/hard state. It also supports our conclusions, from other studies, that accretion and jet production are strongly linked and that the source of the jet must be in the accretion flow itself. However, the JDADF model does not address the *physics* of either accretion *or* jet-production, let alone show how these two might be connected in an integrated physical model of the central engine.

Key X-ray Timing Observations

Timing observations of accreting, jet-producing sources give perhaps the best insight into the behavior and structure of the jet-producing disk in the plateau state. The power spectra of these sources in the plateau state contain low frequency noise that is bandwidth limited (ranging only from $\sim 0.1 - 1$ Hz) with a power-law falloff above a break frequency ν_{br} . Somewhat above that break is a single quasi-periodic oscillation or QPO.

The existence of bandwidth limited noise, however, is rather *inconsistent* with the ADAF concept. An optically thin, geometrically thick ADAF that is driven by the MRI should display its internal structure in the power spec-

trum of the source. That is, in the X-ray band one should be able to see deep into the accretion flow and observe the turbulence throughout the ADAF region. Specifically, if the ADAF were to extend from the transition radius down to near the radius of the compact object, then one would expect to see *broad* band noise, extending from the dynamical frequency at the transition radius (0.1 Hz at $10^3 R_{Sch}$ for a $10M_{\odot}$ black hole) up to that near the surface of the compact object (~ 1 kHz at $6 R_{Sch}$). The fact that the noise is very bandwidth limited indicates that the ADAF may extend over only a rather narrow range of radius near r_{tr} .

Another important timing observation is that low-frequency QPOs (particularly the type “C” ones) occur *simultaneously* with jet production. (See the paper by R. Remillard in these proceedings.) This is true of both the black hole low/hard state and the atoll island state. Apparently, the LFQPO and jet production in the disk are closely related.

QPOs in both X-ray binaries and in cataclysmic variable stars have striking similarities [36]. In the latter case the QPOs and related oscillations are thought to arise from traveling wave structures in the magnetized accretion flow. In the case of black holes and weakly magnetized neutron stars the magnetic field would have to be provided by the disk itself, rather than the compact object. Indeed, spiral magnetic structures appear to arise in the center of MRI accretion flow simulations [16]. However, as noted above, such simulations do not show global magnetic field structures nor the MHD wind/jet outflow that appear to be associated with the existence of a QPO.

Another important clue to the structure of the central engine is that the frequencies of the LFQPO and noise break are tightly correlated, with $\nu_{QPO} \sim 8\nu_{br}$ [37]. That is, the QPO occurs at a frequency somewhat higher than the majority of the bandwidth-limited noise. If the QPO frequency is related to the local disk dynamical frequency where the oscillation is produced, then that oscillation, and possibly the jet production that appears related to it, appear to occur in a relatively less noisy region of the central accretion flow.

A final, possibly-important, observation concerns the ability of neutron star (atoll) sources to produce jets compared with that of black hole candidates. For the *same accretion rate*, island atoll sources appear to produce ~ 30 times weaker jets than black hole candidates [24]. This implies that some property of the black hole is an important factor in producing a jet. The two obvious properties possessed by the latter and not the former are an horizon and an ergosphere. As electrodynamic jet-production models create jets via rotation, the existence of a strong, frame-dragging ergosphere appears the more likely candidate, but exactly how it plays a role is not yet clear.

TOWARDS AN INTEGRATED ACCRETION/JET-PRODUCTION MODEL

How does the accretion flow develop well-ordered magnetic fields (which are necessary to produce jet outflows) from an otherwise turbulent ADAF-like structure? And what accretion morphology and processes might explain many of the above X-ray and radio flux and timing observations? The following discussion presents a suggested direction in which future work might proceed, based on the above theory and observations.

Basic Magnetically-Dominated Accretion Flows

It seems clear that, in order for jet production to occur, and in order to suppress the broad band noise that an extensive ADAF should produce, the flow must transition from MHD turbulence to a well-ordered magnetized flow, either in the disk corona or in the disk itself. One way in which this may occur has been suggested by Krolik [14] for the ‘plunging’ region inside the innermost stable circular orbit of a black hole: as material nearly free-falls toward the compact object, magnetic stresses must become dominant. In the language of plasma physics, the plasma β (ratio of gas pressure stresses to magnetic stresses) must decrease with radius.

Now, ADAFs are in near free fall as a natural byproduct of a high α and geometrically thickness: the accretion velocity is a substantial fraction of the free fall speed [25]. Furthermore, the magnetic stresses in an ADAF are also already comparable to the gas pressure stresses ($\alpha \sim 1$). Therefore, *the nearly plunging advection-dominated accretion flow is possibly unstable to forming a magnetically-dominated flow along rather laminar, strong field lines.* If we take $\beta \sim 1$ near r_{tr} , then the plasma parameter should scale with radius as

$$\begin{aligned} \beta &\equiv \frac{p_{gas}}{B^2/8\pi} \approx \beta(r_{tr}) \frac{(r/r_{tr})^{-5/2}}{(r/r_{tr})^{-4}} \approx 1.0 (r/r_{tr})^{3/2} \\ &\rightarrow \leq 0.001 \end{aligned} \quad (2)$$

As pointed out by Krolik, neither free-fall nor force-free are good approximations. Near r_{tr} the still-turbulent infalling matter still will jostle the field lines there, and the orbital motion of the accretion will give a spiral character to the flow. But, well inside r_{tr} the magnetic field will dominate the stresses (gravity included) forming an essentially force-free structure. (See Figure 3.)

A number of properties of such a magnetically-dominated accretion flow or MDAF can be identified:

- If the central object is a rotating black hole, the field

will attach itself to the hole’s ergosphere in several free-fall times. If it does not, the accreting matter will build up at a radius outside the ergosphere, then once again dominate the magnetic stresses, re-initiate the turbulent advection-dominated flow, and continue to draw the field in closer to the hole until the field does reach the ergosphere.

- Like the solar corona, the force-free magnetic structure set up will have large-scale field lines, some of which close near the compact object and some of which break open above the disk.
- As the accreting matter slips along the closed field lines toward the hole, it will transfer its angular momentum outward *solely by magnetic stresses*. The effective α will be much greater than unity ($\approx \beta^{-1} \sim 10 - 100$), so the transport will be quite efficient. This will produce an over-abundance of angular momentum near r_{tr} that must be carried away either by MHD turbulence (into the outer SS disk) or by an MHD wind. *It is proposed that the base of the jets so often seen in the plateau state looks something like the picture in Figure 3*, lying in an MDAF just interior to an ADAF torus.
- There are two possible sources of quasi-periodic oscillations at roughly the orbital frequency somewhat inside r_{tr} : a) If the magnetic inflow breaks up into spiral converging flux tubes, as has been seen near the center of global MRI simulations [16], then the rotation of those accretion flux tubes could produce QPOs; b) Similarly, if the open field lines form coronal holes, then their rotation also could produce quasi-periodic oscillations. Either way, the dominant emission should be nonthermal, produced by charged particles trapped in the rotating field lines.
- A QPO frequency of 0.01 – 10 Hz is consistent with the Keplerian frequency at a transition radius of $r_{tr} \sim 10^{2-3} R_{Sch}$ for a $10M_{\odot}$ black hole.

Advantages of MDAFs

MDAFs have a number of advantages that better explain some properties of accreting, jet-producing sources than ADAFs alone:

- If QPOs are produced by rotating flux tubes that also produce the jet outflow, then the type ‘C’ QPOs that are associated with jet production may be the ‘blade of the jet engine turbine’.
- Heating of the accreting plasma within the MDAF will be only by compressional heating, not turbulence. This will potentially remove a possible source of coupling between electrons and ions, al-

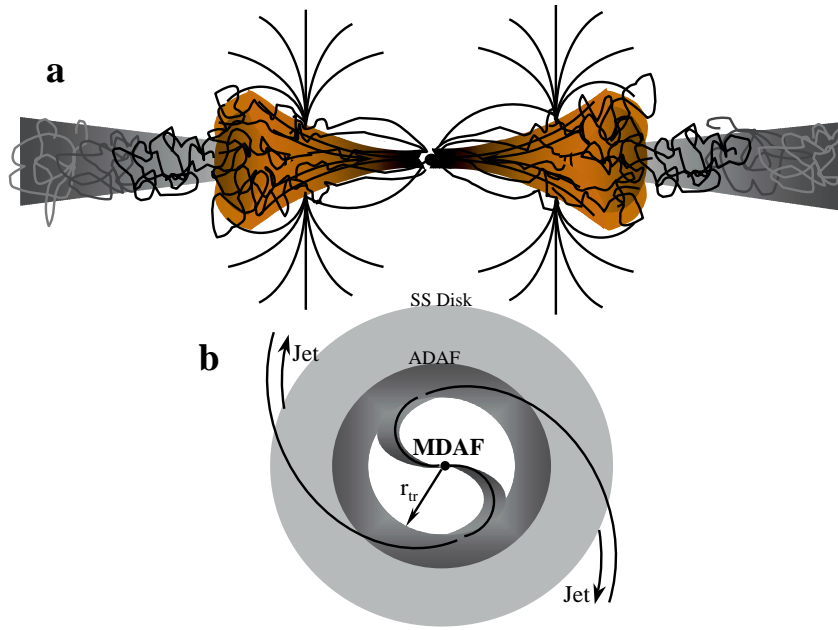


FIGURE 3. Schematic edge (a) and top (b) views of an MDAF. The central region of the ADAF has given way to a *laminar*, magnetically-dominated inflow, leaving the ADAF to occupy only a toroidal region near r_{tr} . Closed field lines potentially can couple to a rotating black hole, while open field lines can drive a steady jet.

lowing two-temperature flows to exist, if they are needed.

- On the other hand, a hot two-temperature accretion flow is no longer needed to maintain the geometrically thick, optically thin hot accretion flow seen in the low/hard state. In an MDAF the magnetic field now provides the support of the plasma against gravity. The ions and electrons can form a one-temperature plasma throughout the MDAF and still satisfy the observations. Even the ADAF torus can be a one-temperature plasma. At $10^{2-3}R_{Sch}$ the virial temperature is $\sim 0.5 - 5MeV$, so a several hundred keV, optically thin outer ADAF torus is still possible even with $T_e \sim T_i$.
- Identification of turbulence in the ADAF torus with the bandwidth-limited low frequency noise explains several properties of the X-ray timing:
 - Low-frequency break ν_{br} : the ADAF is only of limited radial, and therefore bandwidth, extent.
 - High frequency fall-off of the turbulence: the interior flow is an MDAF in this case so higher frequency MRI turbulence is successively suppressed towards smaller radii.
 - Correlation of ν_{br} with ν_{QPO} : Both are produced near r_{tr} , for any \dot{M} . The fact that $\nu_{QPO} >$

ν_{br} suggests that the QPO may have its origins in the inner MDAF flow rather than the actual MHD jet/wind acceleration region.

- When the MDAF enters the ergosphere, the accreting plasma will be dragged in the direction of the black hole rotation. If it carries the field with it, then angular momentum and rotation energy of the black hole will be transferred to the field, and ultimately back to the transition radius where the jet is being produced. This direct magnetic coupling to the black hole spin may explain why black hole XRBs tend to produce much stronger jets than neutron star sources: as in the classical Blandford-Znajek process, electromagnetic coupling of the disk to the black hole will transfer a significant amount of angular momentum and energy outward to the disk, driving a much stronger jet.

Relation to the Galactic Center Flares

In fact, there are two opposing viewpoints on what might happen when the MDAF enters the ergosphere of a rotating black hole. On the one hand, in the MHD approximation, the matter and field are fully coupled. The frame dragging that must occur in the ergosphere,

then, will force the field to be wound up like a spring. This cannot continue forever, so at some point the field must break and reconnect, creating a large flare near the ergosphere. On the other hand, if the plasma is very resistive, the breaking and reconnection may occur on short time scales, allowing the plasma to flow through an essentially force-free, stationary field structure. Steady ohmic heating will dominate in this case, leading to steady emission from the ergosphere.

Whether one of these two extremes, or some intermediate state, obtains is unclear at present. However, recent observations of infrared flares in the Galactic Center [9] may provide some clues. Two flares, separated by about one day, were observed in the near infrared in June, 2003. Each flare lasted a little over one hour and produced several QPO oscillations at a period of 17 minutes. Such a QPO period for a $3.6 \times 10^6 M_\odot$ black hole is much too short to occur at several hundred Schwarzschild radii and, so, cannot be of the low-frequency type associated with jet production. They must be produced very close to the black hole itself. Such flares appear to occur more or less continuously at the rate of a few per day.

It is proposed here that the flares are produced by reconnection events in the ergospheres of the rotating Galactic Center black hole. The duration of the flare represents the period of time during which the MDAF remains attached to the ergosphere, and the period of the QPO, then, is identified as the rotation rate of the ergosphere. This conclusion is significantly different from that of [9], who suggested that the QPO represented the period of the last stable orbit. Curiously, a black hole of this mass, whose rotation period is 17 minutes at the equatorial radius of the ergosphere (the ‘static limit’) has an angular momentum parameter of $j \equiv J/(GM/c) \approx 0.5$, similar to that estimated by [9] by equating this to the period of the innermost circular orbit. The period of the infrared QPOs in Sagittarius A, therefore, appears to be close to that predicted when the innermost stable orbit and static limit are in rotational lock.

CONCLUSIONS

The MDAF is the natural physical extension of the ADAF+SS disk scenario for the low/hard state of accreting, jet-producing compact objects. Its purpose is to integrate accretion and jet production into a single physical theory. The MDAF includes features from a number of past works, but some new features of its own. It has enough phenomenological success in qualitatively explaining many observations of XRBs and AGN to be considered seriously as a possible accretion model. However, phenomenology does not a model make. Much more quantitative work is needed to see if MDAFs are

a truly viable model for jetted sources.

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